A RELATIONSHIP BETWEEN FREQUENCY DEPENDENT ULTRASONIC ATTENUATION AND POROSITY IN COMPOSITE LAMINATES

M.S. Hughes*, S.M. Handley*, J.G. Miller, and E.I. Madaras**

Physics Dept. Washington University*, St. Louis, MO 63130

NASA Langley Research Center**, Hampton, VA 23665

INTRODUCTION

The detrimental effects of porosity on material strength are well known. The work of Hsu, Rose, and Adler[1] provides a means of estimating the volume fraction of pores and the average pore radius in isotropic elastic media from the value of frequency at which the attenuation coefficient becomes frequency independent and the magnitude of the attenuation coefficient at that plateau. Quantitative results for the isotropic case depend on numerical factors obtained by Gubernatis et al.[2] which are functions of the ratio of the transverse to longitudinal sound velocities, i.e., on the Poisson ratio. Mobley et al.[3] have tested these theories by making measurments of attenuation covering a frequency range that extended well into the frequency independent plateau. The experimental results of these investigators suggest that the theoretical results obtained by Rose et al. are qualitatively correct even though some of the features of wave propagation in layered, anisotropic media are not explicitly incorporated into the scattering model.

We consider an approach to deal with the case of anisotropic media, in which the magnitude of the attenuation may preclude making measurements at sufficiently high frequencies to reach the plateau region. A well-known experimental result for frequencies lower than that corresponding to the plateau is that the attenuation coefficient exhibits an approximately linear increase with frequency over a range from f_{low} to f_{high}. Typically the useful bandwidth of the measurement is substantially smaller than this range and falls at an unknown location between these limits. Fortunately, the expression for the attenuation coefficient contains numerical factors which depend only weakly on the ratio of f_{high} to f_{low}, varying only by a factor of 3 for the ratio of f_{high} to f_{low} ranging from 10 to 1 to 10,000 to 1. In the case of composites with complex lay-ups for which a detailed theory that describes the effects of porosity on attenuation may not be available, empirical knowledge of these numerical factors obtained from laminates of known porosity might provide an approach for estimating the porosity from ultrasonic measurements of similar composites. Approaches to materials characterization based on the frequency dependence (slope) of attenuation are widely employed in medical ultrasonics.[4] Recent investigations by Nair et al.[5] and Tittmann et al.[6] suggest the feasibility of applying these methods to estimate the volume fraction of porosity in composite laminates.

To evaluate this approach we measured the slope of attenuation as a function of frequency in a set of 4 glass-fiber/epoxy-matrix test specimens with simulated porosity (glass spheres) ranging from 1% to 12% (volume fraction) and a set of 5 uniaxial graphite-fiber/epoxy-matrix specimens with simulated porosity (glass spheres) ranging from 1% to 8%. Good correlation was obtained between the measured slopes and porosity in each case, suggesting that semi-quantitative estimates of porosity can be achieved without measurements in the plateau region and without a quantitative theory.

EXPERIMENTAL METHODS

SAMPLE PREPARATION

The effects of porosity were simulated using solid glass beads, 75 to 150 microns in diameter, in 16 ply uniaxial graphite-fiber/epoxy-matrix composites. These composites were fabricated using 5208-T300 prepreg tape. Measured amounts of glass beads were introduced between the 12th and 13th layers during the lay-up of a 12 by 16 inch composite. The beads were dusted onto circular regions 2 inches in diameter at sites on a square grid with centers 4 inches apart. The sample was autoclaved and cured in an oven using a standard cure protocol. The 12 by 16 inch sample was cut into smaller samples (approximately 3.75" by 3.75") so that each contained a single zone of "porosity" with a volume fraction of 1%, 2%, 4%, 6%, or 8%.

MEASUREMENT METHODS

The signal loss was measured in transmission mode with a specimen placed in the overlapping focal zones of a matched pair of 25 MHz center frequency, 0.25 inch diameter, 1 inch focal length transducers. Each sample was scanned on a 21 by 21 grid in 1 mm steps and the acquired frequency spectra averaged to reduce the effects of spatial variations of "porosity" within the samples.

The measurement system used for data acquisition is illustrated schematically in Figure 1. The transmitting and receiving transducers were oriented so that the insonifying beam was perpendicular to the surfaces of the sample and were aligned by viewing the received signal on a spectrum analyzer. A Metrotek MP215 wideband pulser was used to drive the transmitting transducer. The output of a MR106 wideband receiver was routed to a stepless gate and the 1.5 μsec gated signal was subsequently used as the input to the spectrum analyzer. A DEC PDP 11/73 running the UNIX operating system was used to control the motor driven apparatus on a C-scan tank (in which the samples were placed for data acquisition) as well as to acquire the data from the spectrum analyzer for storage and subsequent analysis.

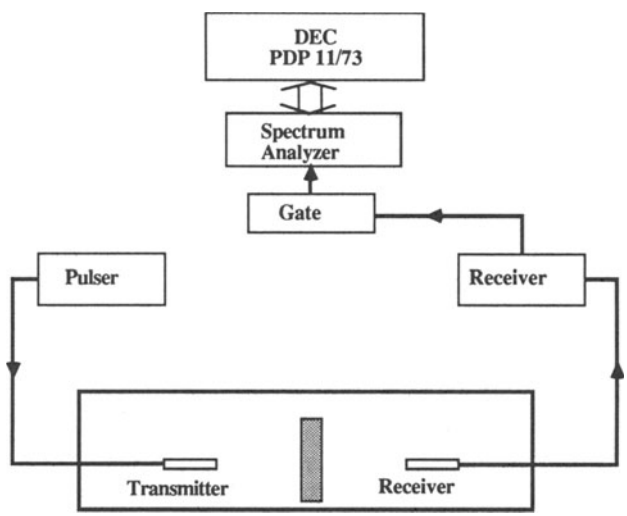

Figure 1: Block diagram of the transmission mode data acquisition system.

DATA ANALYSIS

The signal loss through the composite laminate was obtained by normalizing the acquired averaged frequency spectrum with a calibration spectrum obtained from a water-only-path trace,

$$\text{Signal Loss} = \log[\text{calibration spectrum}] - \log[\text{sample spectrum}] . \qquad (1)$$

This method of log spectral subtraction is performed to deconvolve effects arising from the electromechanical response of the transducers and front-end electronics from the sample spectrum. The normalized data were analyzed by performing a Taylor expansion around the center frequency f of the useful bandwidth,

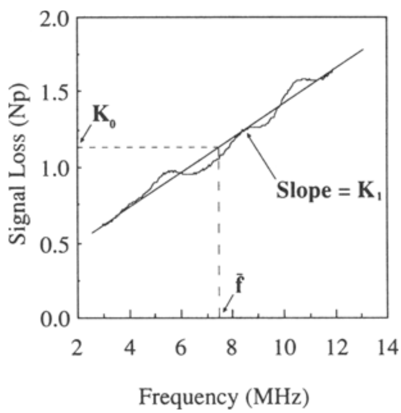

Figure 2: Plot displaying a typical signal loss and the corresponding Taylor expansion given by Equation(2).

$$\text{Signal loss} \approx K_0 + K_1 \times (f - \bar{f}) \qquad (2)$$

where K_0 is an estimate of the average signal loss over the useful bandwidth, and K_1 is the rate of change of the signal loss with respect to frequency. This procedure is illustrated in Figure 2 where the signal loss of a typical spectrum is plotted as a function of frequency along with the appropriate Taylor expansion. The useable bandwidth of this system was 3 to 12 MHz, where the upper limit was due to the increasing attenuation coefficient as function of frequency exhibited by the composite laminates.

METHOD VALIDATION

In order to validate our methods, measurements were made on a set of 5 glass-fiber/epoxy-matrix composites containing controlled amounts of simulated "porosity" (0%, 1%, 3%, 6%, or 12% volume fraction). The glass fibers were approximately 12 μm in diameter and four to five centimeters in length. The fibers ($\rho = 2.43 \pm 0.09$ gm/cm^3) were layed-up by hand in an epoxy resin matrix ($\rho = 1.10 \pm 0.01$ gm/cm^3). Porosity was simulated by the random inclusion of solid lead-glass spheres ($\rho = 2.47 \pm 0.04$ gm/cm^3) drawn from a distribution with radii ranging between 37 μm and 75 μm. These test samples were fabricated with a fiber volume fraction of approximately 8%. One sample was fabricated without glass beads in order to serve as a control.

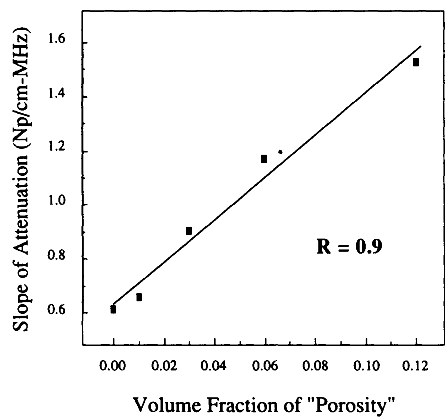

Figure 3: Validation of the proposed method. Preliminary experiments were performed on glass-fiber/epoxy-matrix composites with controlled amounts of "porosity" (simulated by solid glass inclusions).

The results of this control study are presented in Figure 3 in which the slope of the attenuation is plotted versus volume fraction of "porosity". The correlation coefficient obtained by performing a linear regression between slope of attenuation and the volume fraction of "porosity" is 0.9, suggesting the potential of the method.

THEORY

Rose has derived an expression for the concentration of hollow spheres embedded in an elastic medium,

$$\text{Conc.} = \frac{4}{3A_2\pi}\int_0^\infty \frac{\alpha(k)}{k^2}\,dk \tag{3}$$

where $\alpha(k)$ is the excess attenuation due to the scattering of sound waves by the pores.[7] That is, $\alpha(k)$ represents the increase in the attenuation produced by the addition of hollow spherical pores

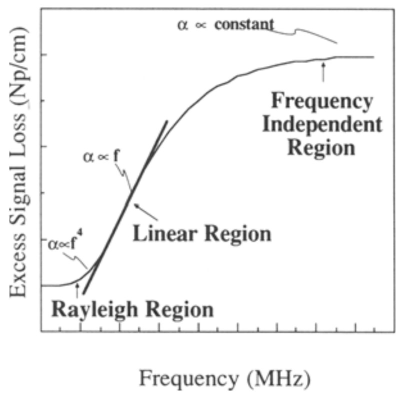

Figure 4: Illustration of the phenomenological model.

to the material above that due to the attenuation from the elastic background medium. We consider the case in which the excess attenuation due to the presence of porosity can be approximated by

$$\alpha(f) = (\text{excess attenuation}) = (\text{excess } K_1) \times \begin{cases} \frac{1}{f_{low}^3} f^4 & f < f_{low} \\ f & f_{low} < f < f_{high} \\ f_{high} & f > f_{high}. \end{cases} \tag{4}$$

as illustrated in Figure 4.

This model implies an f^4 dependent Rayleigh scattering in the low frequency region, and a frequency independent geometrical scattering in the high frequency region. The approximately linear dependence on frequency in the intermediate region is well supported from experimental measurements performed on composite laminates. Because of the finite useable bandwidth of the experimental apparatus, both f_{high} and f_{low} are usually unknown. Nevertheless, the relationship between the volume concentration of porosity and excess K_1 is only weakly dependent upon the ratio of f_{high} to f_{low}.

Inserting Eq.(4) into Eq.(3) leads to

$$\text{Conc.} = \frac{4}{3A_2\pi} \times \frac{V}{2\pi} \times (\text{excess } K_1) \times \left\{ \frac{1}{f_{low}^{\;3}} \int_0^{f_{low}} f^2\, df + \int_{f_{low}}^{f_{high}} \frac{df}{f} + \int_{f_{high}}^{\infty} \frac{f_{high}\, df}{f^2} \right\} \tag{5}$$

or

$$\text{Conc.} = (\text{excess } K_1) \times \frac{4}{3A_2\pi} \times \frac{V}{2\pi} \times \left[\frac{1}{3} + \ln\left[\frac{f_{high}}{f_{low}} \right] + 1 \right] . \tag{6}$$

It is convenient to express this result as

$$\text{Conc.} = (\text{excess } K_1) \times \text{Velocity} \times [\textbf{Numerical Factor}] \;, \tag{7}$$

where

$$\textbf{Numerical Factor} \equiv \frac{4}{3A_2\pi} \times \frac{1}{2\pi} \times \left[\frac{1}{3} + \ln\left[\frac{f_{high}}{f_{low}} \right] + 1 \right] . \tag{8}$$

The **Numerical Factor** is a slowly varying function of the ratio f_{high}/f_{low} over several decades, as illustrated in Figure 5. Because f_{high} and f_{low} are rarely known, this slow variation is the basis for the predictive usefulness of the model.

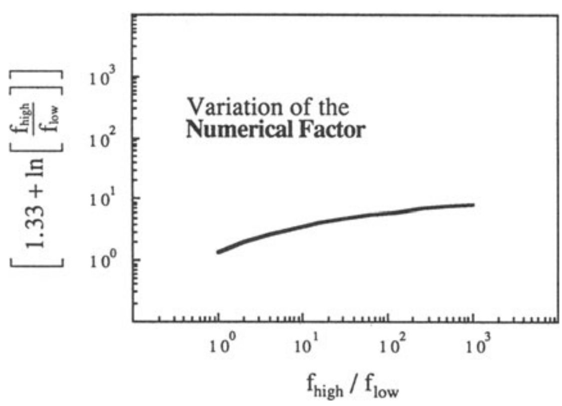

Figure 5: Plot illustrating the slow variation of the **Numerical Factor** as a function of the ratio f_{high} to f_{low}.

RESULTS and CONCLUSIONS

The results obtained for the graphite-fiber/epoxy-matrix specimens are displayed in Figure 6. The scatter plot displays the resultant slope of attenuation (from the spatially-averaged normalized spectrum) for each of the five samples versus the volume fraction of "porosity" for that sample. The slope of attenuation correlates well (r = 0.9) with concentration of "porosity". An examination of Equation(7) indicates that the value of the **Numerical Factor** for the composite laminates under investigation can be determined from the slope of the "Slope of Attenuation" versus the "Volume Fraction of Porosity" correlation plot,

$$\textbf{Numerical Factor} = \left[\text{Velocity} \times \text{Slope of} \begin{Bmatrix} \text{Slope of Attenuation} \\ \text{versus} \\ \text{Vol. Fraction of Porosity} \end{Bmatrix} \right]^{-1} . \tag{9}$$

For the glass-fiber/epoxy-matrix composites used to validate our procedure the value of the **Numerical Factor** was found to be ≈ 0.5 and for the graphite-fiber/epoxy-matrix composites studied the value for the **Numerical Factor** was found to be ≈ 2. The good agreement between the experimental data and the phenomenological model suggests that this approach may be useful in estimating concentrations of porosity in composite laminates.

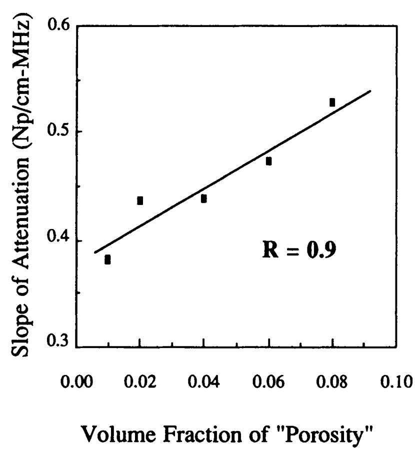

Figure 6: Correlation plot for measurements on graphite-fiber/epoxy-matrix composites.

References

1. J. H. Rose, D. K. Hsu, and L. Adler, ''Ultrasonic charactorization of porosity using the Kramers-Kronig relations,'' *Journal De Physique*, vol. 46, pp. 787-790, 1985.
2. J.E. Gubernatis, E. Domany, J.A. Krumhansl, and M. Huberman, *The Fundamental Theory of Elastic Wave Scattering by Defects in Elastic Materials: Integral Equation Methods for Application to Ultrasonic Flaw Detection,* Materials Science Center, Cornell University, Technical Report 2654, Ithaca, NY, 1976. Unpublished.
3. L. Adler, J. H. Rose, and C. Mobley, ''Ultrasonic method to determine gas porosity in aluminum alloy castings: theory and experiment,'' *J. Appl. Phys.*, vol. 59, pp. 336-347, 1986.
4. D. K. Hsu and S. M. Nair, *Evaluation of porosity in graphite-epoxy composite by frequency dependence of ultrasonic attenuation*, pp. 1185-1193, Plenum Press, New York, 1986.
5. S. M. Nair, ''Quantitative evaluation of porosity in graphite-epoxy composites using the frequency dependence of ultrasonic attenuation,'' *Masters Thesis (Iowa State University, Ames, Iowa)*, 1986 .
6. B. R. Tittmann, B. Hosten, and M.Abdel-Gawad, ''Ultrasonic attenuation in carbon-carbon composites and the determination of porosity,'' *Proceedings of the 1986 IEEE Ultrasonics Symposium*, pp. 1047-1049, 1986.
7. J. H. Rose, *Kramers-Kronig relations and the ultrasonic characterization of porosity in Review of Progress in Quantitative NDE,* Plenum Press, New York, 1985.